Modeling of the Minimized Two-Phase Frictional Pressure Drop in a Small Tube with Different Correlations

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Abstract

Differences between the predicted and experimental frictional pressure drop of two-phase flow in small tubes have frequently been discussed. Factors that could have contributed to that effect have been attributed to the correlations used to model the flow, some being modified from the originals developed for a macro system. Experimental test-rigs have varied in channel geometry, refrigerant type, and flow conditions. Thousands of data have been collected to find a common point among the differences. This paper reports an investigation of different two-phase friction factor correlations used in the modeling of the frictional pressure drop of refrigerant R22. Laminar and turbulent flow regimes have been considered. Minimum friction factor and minimum frictional pressure drop under a common platform - optimized conditions of the mass flux and vapor quality - are searched for using genetic algorithm. The results show that a larger pressure drop is expected with a smaller channel with a large discrepancy between the correaltion that does not consider surface roughness and that which does, as well as between laminar and turbulent flow condition.

Keywords. two-phase flow; friction factor; pressure drop; optimized

Introduction

Classical optimization procedure, experimentally or numerically, which entails discrete variations of the variable of interest over a limited range of set parameters involves a large amount of time and cost. Lately, genetic algorithm (GA), a fast random search mechanism based on the mechanics of natural selection, survival of the fittest, has gained popularity in optimization of processes, components, and systems, most recently in small devices such as the microchannel heat sink (MCHS)[1-3]. This study reports the outcomes of a single objective optimization using GA to predict the minimized two-phase friction factor and frictional pressure drop of cholorodifluoromethane (R22) using different correlations of the friction factor. Although this refrigerant is being phased out due to its hazardous effects on our environment, it is being used here due to the availability of experimental data needed for comparison purposes. Investigation on new potential refrigerants is currently being done experimentally to explore their capabilities but such test-rigs are generally expensive and limited to a range of design and operating conditions. Large discrepancies between the predicted and experimental pressure drop have been reported earlier [4]. Both laminar and turbulent flows are considered here. This fast optimization algorithm introduces a new approach in identifying optimized conditions in two-phase flow analysis.

Methodology

The homogeneous equilibrium model is assumed where the liquid and vapor phase have the same velocity. The frictional pressure drop is given as a function of the friction factor, f_{2ph}, tube length, L,tube diameter, D, mass flux, G_{2ph}, and density, ρ_{2ph},

$$\left(\Delta p_{2ph}\right)_{fric} = 2f_{2ph} \cdot \frac{L}{D} \cdot \frac{G_{2ph}^2}{\rho_{2ph}} \quad , \tag{1}$$

where the Darcy friction factor, f_{2ph}, for laminar flow in a smooth channel is inversely proportional to the two-phase Reynolds number, Re_{2ph},

$$f_{2ph} = \frac{64}{Re_{2ph}} \tag{2}$$

Reynolds number is a function of the channel diameter, mass flux and two-phase viscosity, defined by,

$$Re_{2ph} = \frac{G_{2ph}D}{\mu_{2ph}} \tag{3}$$

For turbulent flow, the Haaland [5], Swamee-Jain [6], Serghides[7] and Blasius [8]friction factor correlations are chosen among many available ones, respectively, they are,

$$f_{2ph} = \left[-1.8log_{10}\left\{\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right\}\right]^{-2} \tag{4}$$

$$f_{2ph} = 0.25\left[log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^{-2} \tag{5}$$

$$f_{2ph} = \left[A - \frac{(B-A)^2}{C-2B+A}\right]^{-2} \tag{6}$$

$$f_{2ph} = \frac{0.079}{Re^{0.25}} \tag{7}$$

where the A, B, and C are function of the surface roughness, ε, D and Re,

$$A = -2log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{12}{Re}\right) \tag{8}$$

$$B = -2log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{2.51A}{Re}\right) \tag{9}$$

$$C = -2log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{3.51B}{Re}\right) \tag{10}$$

For the homogeneous model, many correlations representing the refrigerant properties exist. In the present study, the Mc Adams [9] equation is used, where,

$$\rho_{2ph} = \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right)^{-1} \tag{11}$$

$$\mu_{2ph} = \left(\frac{x}{\mu_g} + \frac{1-x}{\mu_l}\right)^{-1} \tag{12}$$

The parameters used in equations (1) through (12) are listed in Table 1 for the operating pressure of 0.7 MPa. These values are experimental values obtained from two-phase flow tests conducted in a 7.6 mm diameter stainless steel tube of 1.07 meter [10] heated electrically at 12923.71 W/m^2. Minimization of the single objective function is completed with MATLAB toolbox [11] where equations (2) and (4) to (7), each are considered individually. Then, minimization of (1) is completed with the friction factor being represented by equations (2) and (4) to (7), again individually. Discrepancies reported between the modeled and experimental pressure drop could reach as high as 100% [4], probably due to the different models assumed and test-rig used. Thus, this study attempts at analyzing the models representing the Darcy friction factor appearing in the pressure drop, under a common platform i.e. optimized conditions.

Table 2. Properties used

Parameter	Value
Mass flux, G	50-350 kg/m^{2}s
Gas phase density, ρ_g	28.843 kg/m^3
Liquid phase density, ρ_l	1246.598 kg/m^3
Gas phase viscosity, μ_g	11.799 μPa.s

Liquid phase viscosity, μ_g	193.647 μPa.s

Results and Discussion

Figure 1 shows the comparison of the minimized friction factor (fD) and pressure drop (dPf2) for the 3 mm and 7.6 mm diameter tube for the friction factor correlations of laminar flow from Hagen-Poiseuille (H-P), and turbulent flow from Swamee-Jain (S-J), Haaland (H), Serghides (Se) and Blasius (Bl). The diameter of 3 mm is the upper limit for a minichannel beyond which the tube is considered as small, not mini. Although the experimental data was obtained for a 7.6 mm diameter tube, optimization has been completed for the 3 mm channel as well to look at the effects of channel reduction on the frictional factor and pressure drop of two-phase flow of R22.

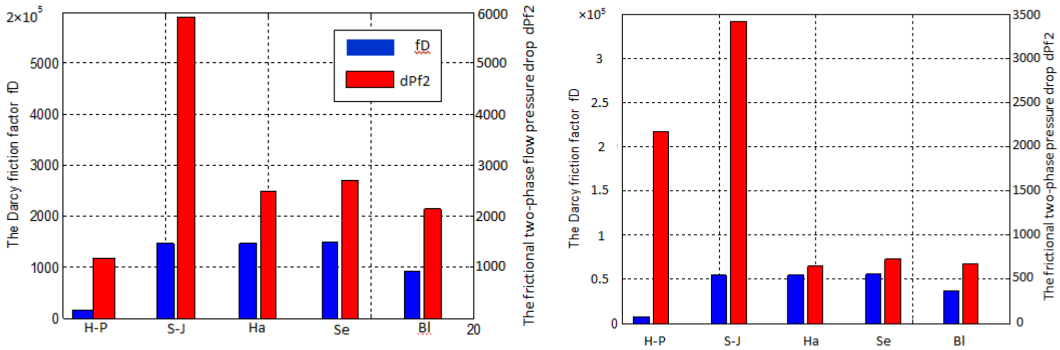

Figure 1. Minimized friction factor and frictional pressure drop for (a) 3 mm tube, (b) 7.6 mm tube.

Optimization with GA has been completed for five runs each for consistency and repeatability, and to obtain the average. The trend in decreasing pressure drop with larger diameter tube is as expected, the pressure drop being more than twice for the 7.6 mm tube compared to the 3 mm minichannel. Minimum pressure drop was found to occur at the lower range of mass flux set, 50 kg/m^2.s for both the 3 mm and 7.6 mm channel for all correlations zero vapor quality. Meanwhile, the lowest friction factor is found to be very close to the saturated vapor state for all correlations attempted, with the optimized mass flux between 341 to 350 kg/m^{2}s for the 7.6 mm tube and between 316 to 350 for the 3mm minichannel. Discrepancies in the friction factor and pressure drop can been seen between the different correlations used, under optimized conditions, with significant difference between the Swamee-Jain correlation and that of Haaland, Serghides, and Blasius correlations. Except for the Blasius, the other three correlations take into consideration the surface roughness factor which has been arbitrarily taken to be 0.03 mm here. However, except for the Swammee-Jain, the difference between the later three correlations is interestingly at a lesser degree with the larger diameter tube. The results here are encouraging since these were obtained using the an evolutionary algorithm which lately have found wide applications in design, transportation and medicine [1-3,12]. The fast output produced show promise in investigation of the hydrodynamic performance of potential new refrigerants.

Conclusion

An evolutionary algorithm based on a random search for a minimized two-phase friction factor as well as frictional pressure drop has been utilized based on different correlations, for laminar and turbulent flow in a small tube. Results have shown that different correlations used produced different outcomes, as has been reported previously though in the present study, the differences under optimized conditions have been obtained quickly with genetic algorithm. As expected the pressure drop is less with a larger diameter tube and significant difference is observed between the Swamee-Jain correlation and the other three correlations investigated. The outcome from this optimization has shown promise due to the quick output obtained in this investigation of the hydrodynamic performance of refrigerant R22. The application of this optimization tool is possible with new potential refrigerants to replace the current hazardous refrigerants.

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